Renewable and Sustainable Energy Reviews 15 (2011) 3603–3607

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Photo-catalytic properties of silicon and its future in photovoltaic applications

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ARTICLE INFO

Article history:
Received 28 March 2011
Accepted 30 May 2011
Available online 19 July 2011

Keywords:
Silicon
Solar
Photovoltaic
Photo-catalytic
Conversion efficiency
Payback time

ABSTRACT

With the possible depletion of fossil fuels in just one generation and the risk of eventual nuclear incidents, the question is whether renewable energy sources have the capacity to replace traditional ones. The availability of solar energy is significantly higher than any other renewable source and silicon is currently the major photo-catalytic material in the solar industry. Conversion efficiency and payback time are noted as key factors, besides atmospheric imperviousness, all of which affect usability of photo-catalytic material. The status and future of Si as a major candidate to take over from traditional sources of energy relies on cost reduction of the high purity Si used as feedstock for solar cell industry, reduced installation costs and network maintenance and development of the next generation of Si solar cells.

Contents

1. Introduction

With oil production estimated to peak as early as 2020, coal reserves for the following 45 years and frequent nuclear incidents, the question is what will be the major energy source in upcoming years [1]. The U.S. Department of Energy [2] estimates approximately $120{,}000 \times 10^{12}$ W of solar power reaches our planet, this is significantly higher than any other energy resource (Fig. 1). Solar energy alone has the potential capacity to meet the planet's entire energy needs since the earth receives more solar energy in an hour than the total energy consumed by humans in an entire year (the rate of current worldwide energy consumption is around 13×10^{12} W). Since 2002, production of silicon for photovoltaic applications has an average growth of 48% each year [3], making the solar energy industry the world's fastest growing energy source with \$37.1 billion in global revenues [4].

The major costs involved in photovoltaic components are modules, panels, arrays, mounting equipment, wiring, inverters, grid connection equipment, service and labor, management and administration costs and permit costs. A summarized cost breakdown for a silicon solar cell can be found elsewhere [5] while a price breakdown for other types of solar cells is difficult to estimate because of low installed capacities and a yet to be determined. Fig. 2 shows that solar grade silicon contributes to about 50% of the cost of a solar cell module. Moreover, module cost contributes to 55% of the final system setup, which brings the contribution of silicon to 25–30% of the final cost. Looking at the energy required for different parts production and system installation, it can been seen that silicon contributes far more than any other component, about 59% (Fig. 2c).

The most important factors and the greatest limitations that determine photovoltaic material sustainability and economical validation are conversion efficiency and energy payback time. While maximum conversion efficiency is related to physical properties

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doi:10.1016/j.rser.2011.05.017

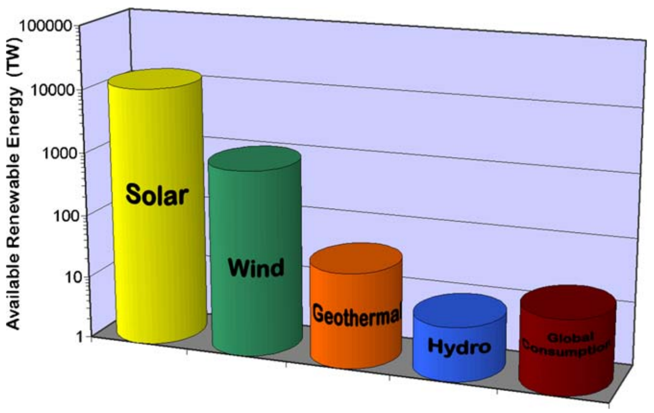

Fig. 1. Available renewable energy and current global human energy consumption. Note logarithmic scale for available energy.

of the photovoltaic material energy payback time depends on available technologies for photovoltaic material production and installation.

2. Conversion efficiency of silicon solar cells

Currently, the vast majority of commercial solar cells are produced out of silicon. Henri Becquerel discovered in 1836 the photovoltaic effect or the capacity of some material systems to generate a voltage when illuminated. Pearson, Chapman, and Fuller from the Bell Laboratories, first reported the modern silicon solar cell in 1954 demonstrating a 5–6% efficiency [7]. In the 1960s, the first commercial solar cells were produced out of silicon. These sells were primary used for powering satellites but were too expensive for other application. The energy crisis in the 1970s initiated considerable technical progress which resulted in significant increase in cell conversion efficiencies and cost reductions due to government support of R&D in alternative energies projects. Nowadays, the efficiency of silicon solar cells under laboratory conditions is approaching the theoretical limit of 29%. Fig. 3 shows the rise in efficiency of laboratory produced solar cell's from the 1950s to present.

Based on their physical properties, the different semiconductor materials or combinations are suitable for only specific spectral ranges. Particularly, silicon transforms 1.4 eV of photons electromagnetic energy into electrical energy. Therefore a specific portion of the radiant energy cannot be used, because some photons do not have enough energy to activate the charge carriers, e.g. photons below 1.4 eV in silicon based solar cells. On the other hand, surplus photon energy is transformed into heat rather than into electrical energy. In addition, there are optical losses, reflections of incoming rays, electrical resistance losses, disrupting influences of material contamination, surface effects and crystal defects, etc. Such losses cannot be reduced or diminished because of inherent physical limits of the materials itself. Therefore, each material has a unique theoretical maximum limit of conversion efficiency, i.e. approximately 29% for crystal silicon.

Research findings have demonstrated efficiencies close to 25% (Fig. 3), while industrially produced solar cells have efficiencies ranging from 12% to 18%. Closing the gap between laboratory and factory efficiencies depends on materials processing innovations, composition and purity of the silicon, process control and better understanding of thermodynamics, phase transformation, kinetics, heat and mass transfer and solid-state physics, etc. Yamaguchi et al. [13] indicated that crystalline Si solar cells will continue to contribute to widespread PV applications as the major PV technology as a result of further development of high-quality and low-cost crystalline Si wafers, high performance and low-cost thin crystalline Si cell process and device technologies based on an understanding of the defects in Si materials and solar cells, process and device physics. Authors also referred to Japanese PV2030 road map, where by the year 2030 efficiencies of 22% for module and 25% for cell technologies into industrial mass production and the wafer thickness to 50–100 μm should be achieved, that will increase the market size by another 100–1000 times.

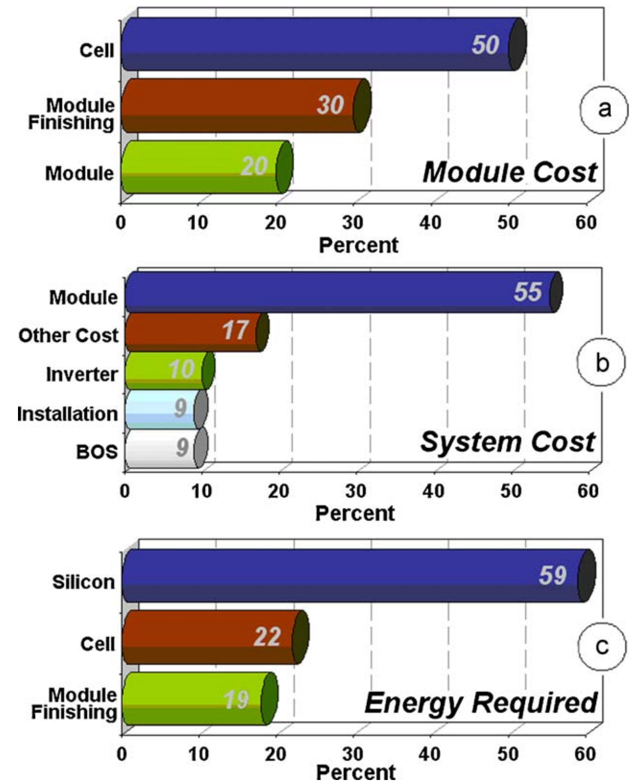

Fig. 2. Cost breakdown of silicon solar cell components [5].

To provide some sense of today's capabilities of silicon based solar cells, the required area of solar cells needed to meet the average consumption of an U.S. residence has been calculated. Under noontime sunshine on a clear summer day, a typical (12% efficient) silicon solar-cell module with an area of 1 m^2 would produce about 100 W of direct-current power. On average over the year, this output could be sustained for about 6 h per day, for a daily yield of about 600 Wh of energy per square meter of installed solar cells.

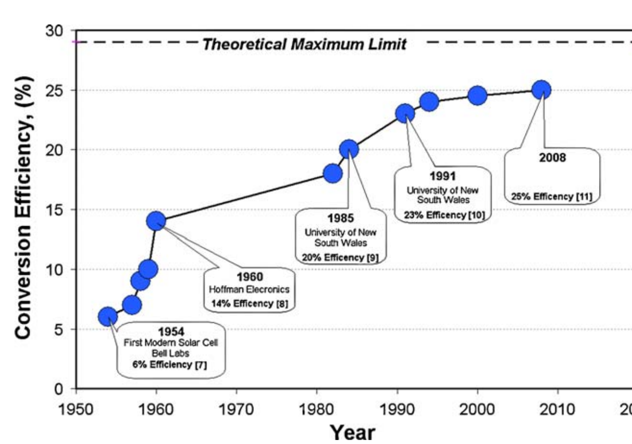

Fig. 3. Energy efficiency improvement in silicon solar cells measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25 °C [12].

The typical U.S. household consumes about 25 kWh of electricity per day, and solar cells comprising about 42 m^2 would be required to provide sufficient power.

Looking in where over presented NREL's chart for best research-cell efficiencies only multijunction concentrators have higher conversion efficiency than silicon. However, the complexity of the concentrators' installation and number of different materials involved in solar cell component contributes to high 'price per watt' ratio for such cells. Particularly, price and availability of Iridium in gallium indium phosphide and gallium indium arsenide cells is major concern. Also, most analysis and service periods estimations were made at 300+ suns that remain to be answered during time and years of service. Recently, much research has been conducted in the third generation or organic photovoltaic material due to low initial price and ease of installation. Conversion efficiency around 5% and sensitivity to atmospheric influences are major drawbacks for such photovoltaic materials. After 2004 due to shortage of the silicon solar cells thin film CdTe cells become the second most common type of commercial photovoltaic material. CdTe panels have slightly lower conversion efficiency (typically 10.5%, maximum 16.5%) than silicon but their ease of the manufacturing, wide wavelength capturing drops their price to less than $1 per watt. Future growth of the thin film panels are limited by Te supply which is an extremely rare element (1–5 ppb in the earth crust) and even bigger concern about the toxicity of Cd oxides and chlorides which are formed on highly reactive cell surface.

3. Energy payback time for silicon solar cells

Advantages of producing electricity with photovoltaic devices are zero emissions and no fossil fuel consumption but the production of solar modules also consumes energy. The period required for a solar cell to produce the same amount of energy that was used to create it, is called the payback time. Due to the many factors influencing quality and lifetime of solar cells, the economy of the solar cells is usually expressed in the payback time rather than in the cost of the solar cell. Due to relatively recent introduction of various photovoltaic materials correlation between calculated and actual energy payback time or ratio between payback time and years of service can only be estimated. However, silicon based solar modules are in commercial use for decades and some systems are in service for more than 20 years with no or minimal maintenance. Such atmospheric resistance and system rigidness is rarely found among known materials.

The most energy consuming part of the silicon solar cell manufacturing process is reduction of silica by carbothermic process and lately purifying/crystallizing silicon by chemical vapor deposition process. An analysis of the payback time for solar grade silicon that had originally been rejected from electronic grade silicon was performed by Alsema [14]. His best estimates of energy used to make frameless PV were 600 kWh/m^2 for single crystal silicon modules and 420 kWh/m^2 for polycrystalline silicon. Assuming a 12% conversion efficiency (standard conditions) and 1700 kWh/m^2 per year of available sunlight energy (the U.S. average is 1800), the calculated payback time is about four years for existing polycrystalline silicon photovoltaic systems. Projecting improvements 10 years into the future, where the author assumes a constant supply of solar grade silicon feedstock by conventional processes and 14% efficiency, energy payback is reduced to about two years.

Furthermore, the U.S. Department of Energy Photovoltaics Program [15] estimates that an average U.S. household producing 1000 kWh of electricity with solar power reduces emissions by nearly 8 pounds of sulfur dioxide, 5 pounds of nitrogen oxides, and more than 1400 pounds of carbon dioxide. During its projected 28 years of clean energy production, a rooftop system with 2-year payback and meeting half of a household's electricity use would avoid conventional electrical plant emissions of more than half a ton of sulfur dioxide, one-third a ton of nitrogen oxides, and 100 tons of carbon dioxide, providing great environmental benefits.

4. Future of silicon solar cells

For some time now, due to the restricted theoretical efficiency at 29% and relatively high initial costs involved in solar grade silicon production due to dependence on chemical vapor deposition processes, it has been thought that either monocrystalline or polycrystalline silicon solar cells would be made obsolete by the eventual introduction of very inexpensive alternative solar cells based on thin films of semiconductors such as cadmium telluride (CdTe), copper–indium diselenide (CIS), or organic photovoltaic materials. This may happen, but so far on the basis reliability, performance and lifetime, none of these alternatives appear to be in a position to challenge silicon solar cells.

Occurrences in the last 10 years indicate an even stronger silicon position for silicon in the photovoltaic market, despite strong marketing approach and commercialization of newly developed photovoltaic materials. In order for any alternative source of energy to gain a significant role in commercial usage a decrease of 'price per watt' value is essential. Although, it is impossible for renewable sources of energies to achieve present per watt value equal to coal, natural gas or nuclear the future increase of price of traditional sources of energy and their influence on environment should be considered. Major steps that have to happen in order for the silicon photovoltaic industry to transform from an alternative to a major source of energy are (i) development of the low energy high capacity processes for Si purification up to standards for solar cell applications; (ii) major involvement of the government and big energy produces and distributors into Si solar cell market that will reduce price of installation and network maintenance; (iii) finally development of the next generation Si solar cells capable of exciting more than one electron and consequently increase conversion efficiency. While the first two steps have direct influence on reduction of energy payback time the last step can set new theoretical limit for silicon conversion efficiency. Lastly, the first and third step rely solely on research and development and fund invested in it.

4.1. Development of the low energy high capacity processes for Si purification up to standards for solar cell applications

Due to the strong demand for silicon photovoltaic applications, producers of metallurgical grade silicon and manufacturers of silicon solar cells have the same interest. For metallurgical grade silicon producers is necessary to find products with higher value and stable demand. At the same time, solar cell manufacturers and distributors are looking for reliable, high capacity and economically viable sources of solar grade silicon. Under the given conditions, it appears that metallurgical grade silicon is a prefect starting material for silicon solar cells where impurity content is only consent (Fig. 4). Merging producers of metallurgical grade silicon with later refining/purifying process handlers can diminish a need for chemical processes and requirements for high initial capital costs. Replacing the conventional Siemens process with a direct metallurgical route can reduce energy payback time for silicon based solar cells several times. Hammond and Gamble [16] estimated that silicon treatment by a direct metallurgical route for production of SGS can be five times more energy efficient than the conventional/commercial processes that use more than 200 kWh for 1 kg silicon produced.

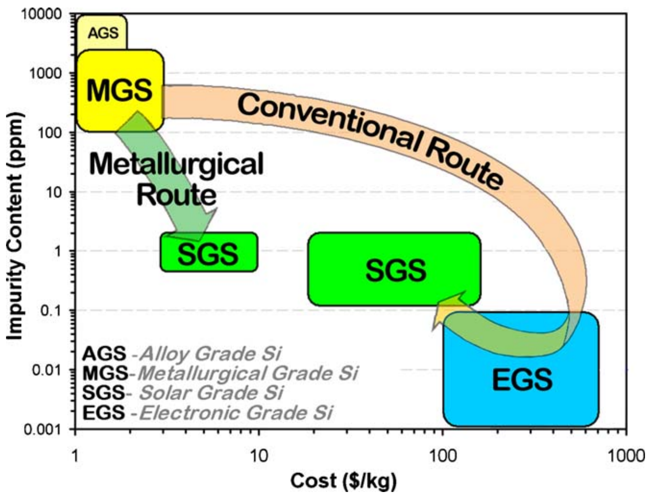

Fig. 4. Relationship between impurity content and the cost of silicon [17].

With the demand for extremely high purity products and the necessity to develop complete new processes, the introduction of this new product into the market involves a great deal of research and the development of new silicon treatment techniques. For many years researcher are attempting to refine silicon using combination of metallurgical techniques, e.g. vacuum treatment, slagging or alloying. Companies such as Calisolar (California) or 6Nsilicon (Canada) already established commercial production of solar grade silicon based on metallurgical refining techniques. Current market price for 'price per WattPeak' for silicon based modules dropped from 6 to 3 US dollars in the last 10 years mainly due to increased capacities and improved quality of the feedstock silicon.

4.2. Reduced installation costs and network maintenance

Beside reduction of production and refining costs, an infrastructure buildup, delivery network and its maintenance is the second key step in reducing the price of alternative sources of energy. Some economists denote that moment when major energy distributors find their economical interest in investments into alternative sources without government substitutes will be transition point for the alternative sources of energies to become major source of energy. Implementing new production and refining techniques for solar grade silicon that already taking a place could reduce the price of a silicon module up to a critical barrier for the transition of the solar cell industry from small contractor businesses into larger companies. Involvement of larger companies and major energy producers and distributors will result in significant cost reduction in other major aspects involved in photovoltaic systems that can initiate a further cost reduction to $1 per Watt [18]. Koot referred that reaching $1 per Watt benchmark will be the turning point from which markets will emerge and grow without any government aid and that could be the transition point for the solar cell industry from the alternative source to a reliable, economical source of energy [19].

4.3. Development of the next generation Si solar cells

Recent research at the nanolevel related to silicon photovoltaic capacities and photo-catalytic properties suggests that theoretical limit in conversion efficiency can be up to 47% which positions silicon at the forefront as a major future component for photovoltaic applications [20]. Today a typical silicon based solar cell generates one electron per photon of incoming sunlight. Conversely, some materials are capable of producing multiple electrons per photon. Excitation of the more than one electron in has been seen for the first time in the National Renewable Energy Laboratory (NREL), in Golden, Colorado where Luke et al. discussed that silicon nanocrystals can produce two or three electrons per photon of high-energy sunlight although such designs remain hypothetical at this point [21,22]. In most silicon solar cells, the extra energy in blue and ultraviolet light is wasted as heat. The effect can lead to a new type of solar cell that utilizes the same feedstock and network as commercial solar cells but that are more than twice as efficient as today's typical silicon based modules. Furthermore, concentrating sunlight could raise that figure to well over 60%. New technology not only gains from the advantages of efficiency inherent in producing different numbers of electrons based on the amount of energy in the striking photon, but a manufacturer does not incur the expensive pure-silicon-crystal-growth processes. Such situation can make silicon produced by affordable, high capacity, entirely metallurgical refined a perfect product.

5. Conclusion

Energy received for the sun has capacity to satisfy energy demand for entire human population. Due to its photovoltaic properties, resistance to atmospheric influence and good mechanical properties, silicon is the major element used for commercial photovoltaic applications today. Although considerable advances are recognized in second or third generation of photovoltaic materials, silicon will stay the major material for photovoltaic applications for decades that are coming. The first step in making solar energy affordable and major source of energy is the development of the new technologies for production of high purity silicon that is feedstock material for solar modules where one possible way could be utilization of metallurgical techniques that have high capacity and low environmental impact in comparison with current chemical techniques for silicon production. Recent price drops of silicon solar cells are indication that the benefits of the undergoing the fist step are evident. Second step is price drop up to level where major energy producers and distributors will gain their economical interest and some examples are evident in developed countries such as Germany, Japan or Canada where solar energy farms are integrated into a major energy supply grid. Can or when solar energy with silicon as major element will became the independent or even major source of energy depends of the future cost and energy reduction in pure silicon production as well as advancement and development of techniques that can utilize excitation of more than one electron from single silicon atom by single high energy photon. In the last 10 years price of the electricity generated by silicon solar cells dropped several times. If similar trend occur in following 10 years silicon based solar energy harvesting can become a major source of energy for majority of human population.

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Further reading

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